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SHOCKS PRODUCED BY JUPITER IN THE CONTEXT OF CHONDRULE FORMATION: EFFECTS OF COOLING AND DUST DENSITIES.

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Introduction: Shocks are one of the major mechanisms invoked to explain the formation of chondrules and their specific properties [e.g. 1]. They can induce fast heating to temperatures needed to melt chondrule precursors (> 1800 K) and allow for subsequent rapid cooling (0.5-3000 K/h). However, the origins of the shocks are still debated. Imaging of protoplanetary disks, for instance by the ALMA (Atacama Large Millimetre/submillimetre Array) telescope, identified large gaps in these disks potentially carved by massive planets [2]. Interactions between a massive planet and the disk create shocks travelling through the disk and large-scale vortices, in which dust can be concentrated, along with enhanced gas density and pressure [3]. These settings provide favourable conditions for chondrule formation, which requires such an environment to explain the retention of volatile species such as Na [4]. The largest regions of high vorticity are located on the outer edge of the gap formed by the planet and can cover areas of up to 1 AU in diameter. They are strongly affected by the shocks produced by shear forces resulting from the planet orbiting at less than Keplerian speeds, while the gas rotates around the sun at such velocities, causing strong friction. To be able to produce chondrules, these shocks must heat particles trapped in vortices to temperatures between 1800 and 2250 K and followed by rapid cooling. This work follows up on previous results [3], in which a Jupiter-mass planet generated temperatures sufficient to melt chondrule precursors. Here, we further explore the role of dust and cooling in the disk in this context.

Methods: The hydrodynamical code ROSSBI [5] was used to perform 2D simulations of the protoplanetary disk and explore the parameter space for shocks that originate from the presence of a massive planet (1 Jupiter mass (MJ)). Simulations include gas and dust, or gas only because the effect of gas drag is negligible over the duration of the runs for small grain sizes relevant to chondrule precursors (µm-sized). To study the influence of the shocks on the pressure and temperature regime of the disk, several parameters were tested and three cases for cooling were investigated: (i) Early simulations did not include a cooling mechanism (adiabatic case). (ii) Thermal relaxation, which applies a cooling function to the disk that depends on local orbit frequency and specifies a number of orbits (τ_c) for temperature variations to return to that of the background if no further disturbances occur. (iii) An approximation of radiation diffusion (κ-cooling) [6], which covers a range of cooling conditions with a smooth and continuous transition between extreme regimes. The cooling conditions depend on local temperature and the local optical depth.

Discussion: We previously showed that temperatures sufficient to melt chondrule precursors can be reached in a disk similar to the solar protoplanetary disk [3]. However, these simulations applied either adiabatic cooling or thermal relaxation with slow cooling rates ($\tau_c \geq 1000$ orbits). With lower values for thermal relaxation ($\tau_c < 1000$ orbits) or κ-cooling, it is difficult to reach temperatures exceeding 1800 K outside the planet's orbit, where vortices are located. When including this more intense, but more realistic, cooling regime, high enough temperatures are only achieved when the planet is very close to the star (~ 1.5 AU), even when considering a more massive planet (2MJ). However, when so close to the star, temperatures inside the orbit of the planet become too high (> 2500 K) to allow for chondrule formation under the effects of shocks propagating inwards and fast local cooling is prevented. Most simulations used the model of the minimum mass solar nebula (MMSN). In simulations adapting a more massive nebula (5MMSN), the planet migrates quickly towards the star (within 200 orbits). While conditions favourable for chondrule formation are achieved during this migration, the interior of the disk strongly heats and prevents the cooling of chondrules. Simulations including dust show that dust fractions (100 µm to 5 mm) will concentrate in vortices, although larger grains concentrate faster than finer ones. The finer grain fractions are also dragged more readily in the shocks, leading to size sorting in the regions affected by the shocks and vortices.

Conclusions: According to the current 2D simulations, chondrule formation in shocks created by Jupiter strongly depends on the cooling conditions considered for the disk. Under the investigated conditions, it seems unlikely that this process could explain chondrule formation in our solar system. The presence of a massive planet can, however, create concentrations of dust and gas in large regions that are favourable to chondrule formation, but this scenario would require an additional energy source to heat the chondrule precursors to adequate temperatures.

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